Evaluation of a telerobotic system to assist surgeons in microsurgery

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This work was done at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration. The RAMS system development is the result of collaboration between NASA/Jet Propulsion Laboratory and Dr. Steve Charles, and MicroDexterity Systems, Inc. The experiment described in detail in this paper was conducted at the Doheny Eye Institute, University of Southern California. We thank our subjects for kindly participating in the experiment.

Abstract:

A tool that assists surgeons manipulate surgical instruments more precisely than is possible manually was developed. The tool is a telemanipulator that scales down the surgeon's hand motion and filters tremor in the motion. The signals measured from the surgeon's hand are transformed and used to drive a 6 degrees of freedom robot to position the surgical instrument mounted on its tip. A pilot study comparing the performance of the telemanipulator system against manual instrument positioning was conducted at the USC School of Medicine. The results show that a telerobotic tool can improve the performance of a microsurgeon by increasing the precision with which he can position surgical instruments but at the cost of increased time to perform the task. We believe that this technology will extend the capabilities of microsurgeons and allow more surgeons to perform highly skilled procedures now only performed by the best surgeons. It will also enable new surgical procedures beyond the capabilities of even the most skilled surgeons.

Keywords:

Telemanipulator, position scaling, assist for microsurgery, performance evaluation

Key links:

http://robotics.jpl.nasa.gov/tasks/rams

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A tool that assists surgeons manipulate surgical instruments more precisely than is possible manually was developed. The tool is a telemanipulator that scales down the surgeon's hand motion and filters tremor in the motion. The signals measured from the surgeon's hand are transformed and used to drive a 6 degrees of freedom robot to position the surgical instrument mounted on its tip. A pilot study comparing the performance of the telemanipulator system against manual instrument positioning was conducted at the USC School of Medicine. The results show that a telerobotic tool can improve the performance of a microsurgeon by increasing the precision with which he can position surgical instruments but at the cost of increased time to perform the task. We believe that this technology will extend the capabilities of microsurgeons and allow more surgeons to perform highly skilled procedures now only performed by the best surgeons. It will also enable new surgical procedures beyond the capabilities of even the most skilled surgeons.

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1. Introduction

Surgical operations on the eye, ear, brain, nerves and blood vessels require precise positioning of surgical instruments because of the minute sizes of features to be manipulated in the surgical field. Surgeons often use a microscope to help them see these features while manipulating the instruments with their hands. Much effort is spent teaching microsurgeons techniques to reduce the tremor in their hands for positioning instruments with great precision and for manipulating them smoothly. In this paper we report on results from evaluation experiments conducted on a telerobotic system that was developed to assist surgeons overcome these limits in their manual dexterity.

Telerobots have traditionally been developed for use in hazardous environments and for space exploration[1]. Their use as tools to help surgeons in microsurgery is a relatively recent[2,3] concept. The Robot Assisted MicroSurgery (RAMS) system[4,5,6] evaluated in this paper allows a surgeon to command motions for a surgical instrument using an input device that precisely measures his hand motions in six degrees of freedom. The measurements are read into a computational sub-system where they are transformed then used to drive a six degrees of freedom robot that holds a surgical instrument. The surgical instrument thus replicates in some fashion the motions entered by the surgeon at the input device in real-time.

Advantages of using this method to control the surgical instrument are:

- The surgeon's hand motions can be scaled down then used to drive the robot holding the surgical instrument thus positioning the instruments more precisely than is possible manually.
- It is possible to remove unwanted motions in the surgeon's hands, for example, eliminating tremor by filtering the signals before using them to drive the surgical instrument.
- Forces sensed at the surgical instrument can be amplified then haptically presented to the surgeon's hands.
- Advanced computer control of routine functions or operator and computer shared control of the telerobotic system based on sensed interaction data or moving within modeled geometrical constraints can improve the performance of a surgeon by reducing the mental or physical effort needed to perform difficult and complex procedures. Examples of this include limiting the maximum force applied at the surgical instrument, automatically tracking a moving surface or limiting motion of the surgical instrument to avoid sensitive tissue.

Development of practical systems for assisting microsurgeons is a growing field of research and commercial interest. Micro-robotic systems developed for biomedical applications have a rich variety of innovations. We list here some of the research recently conducted in this area. Hunter et al.[7] described a parallel-link design of a five degrees of freedom telerobotic system and its associated controls and virtual environment capable of extremely precise positioning. A magnetically levitated telerobot developed by Salcudean, et al.[8], utilized a macro positioning robot with a mini- master-slave telerobot mounted on its tip for precise microsurgery. Dario, et al.[9] described a tethered microrobotic capsule with miniature robot arms designed for travelling up the colon for use in colonscopy. Hannaford, et al.[10] reported on a voice-coil actuated manipulator design for long range teleoperation with micrometer precision control in protein crystal growth experiments. A two-fingered manipulation system used to grasp objects 2 microns in size was developed by Tanikawa, et al[11]. Much effort is spent developing robotic systems for surgery but relatively little has been devoted to quantifying the benefits of them in controlled experiments. Qualitative assessment of benefits of prototypes developed in practical applications provides an independent measure of the potential of new technology. Although there is increasing activity in the research and development of telemanipulation systems for microsurgery, we are not aware of any other human performance experiments with randomized variables and multiple subjects conducted to compare a micro-surgical telerobotics system against manual performance. The work that is reported in this paper is an attempt to validate the utility of the RAMS research prototype by performing a pilot experiment to compare the performance of the RAMS system against a purely manual method of performing precision instrument positioning. We have attempted to determine the benefits of a telerobotic tool for precise positioning of instruments.

There have been many well-designed experiments on human performance in manual control reported in recent years. The experimental procedure reported in this paper is similar to procedures others have used in evaluating human performance. In one study, a comparison of the effect of different control modes on operator performance was conducted. In the experiment, multiple subjects used a teleoperation system designed for space applications to perform a peg-in-hole-insertion task[12]. Similar evaluation of results were used in a study comparing telerobotic control of a laparoscopic camera using the AESOP system against manually controlling the camera[13]. Tendick, et al.[14] studied imaging systems in a knot-tying task. They concluded based on analysis of variance (ANOVA) that direct viewing was superior in performance but comparable in time taken to complete tasks when compared to three other videoscopic system modalities. Adelstein and Ellis[15] studied the effect on human spatial situation awareness of the addition of roll control in addition to pan and tilt control in the viewing of a remote or a computer-synthesized scene. Their results from ANOVA indicated that their subjects performed equally well without and with the roll control.

The RAMS system is a telerobot with mechanical robot arms interacting with the environment and the surgeon's hands under the control of computers. Elements of the RAMS system consist of mechanical, electronics, real-time control and user interface software sub-systems. These are briefly described in section 2. An experiment conducted on the RAMS system at the USC School of Medicine is described in section 3. Section 4 reports on the results from the tests and concludes with a discussion of the current state of the work and future prospects.

2. Telemanipulator System Description

A drawing of the components of the RAMS system is shown on Figure 1. The surgeon holds the handle of the master input device as he would a surgical instrument. The master device is used to command motions for the slave-held instrument. Hand motions are read into the real-time computing system where they are processed, then used to drive the slave robot.

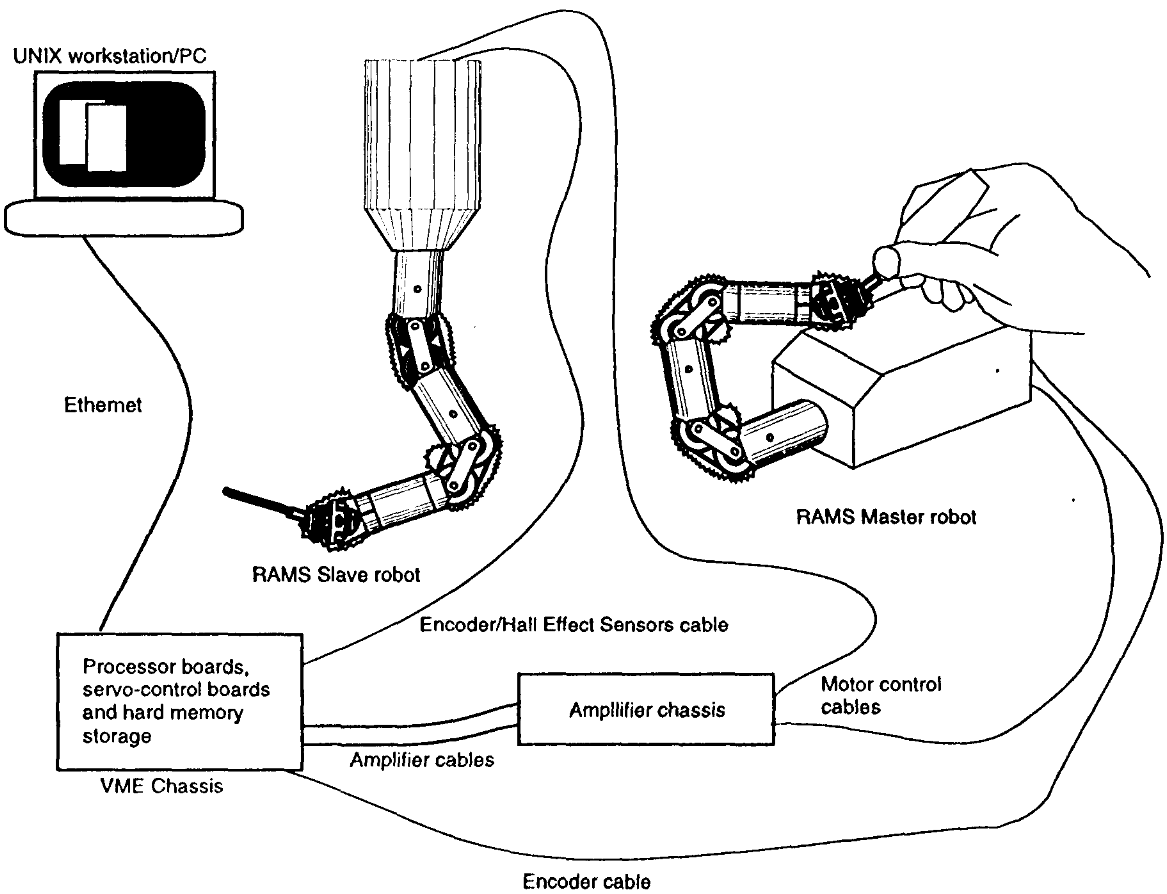

Figure 1 Components of the RAMS system.

A graphics user interface implemented on a workstation (and on a laptop PC for field testing) is used to configure the parameters of the system, for example, setting ratios for position scaling. The components of the engineering system can be classified into 4 sub-systems – the mechanical sub-system, the electronics sub-system, the servo-control sub-system and the configuration and user interface software sub-system. The block diagram in Figure 2 illustrates the interactions between the sub-systems.

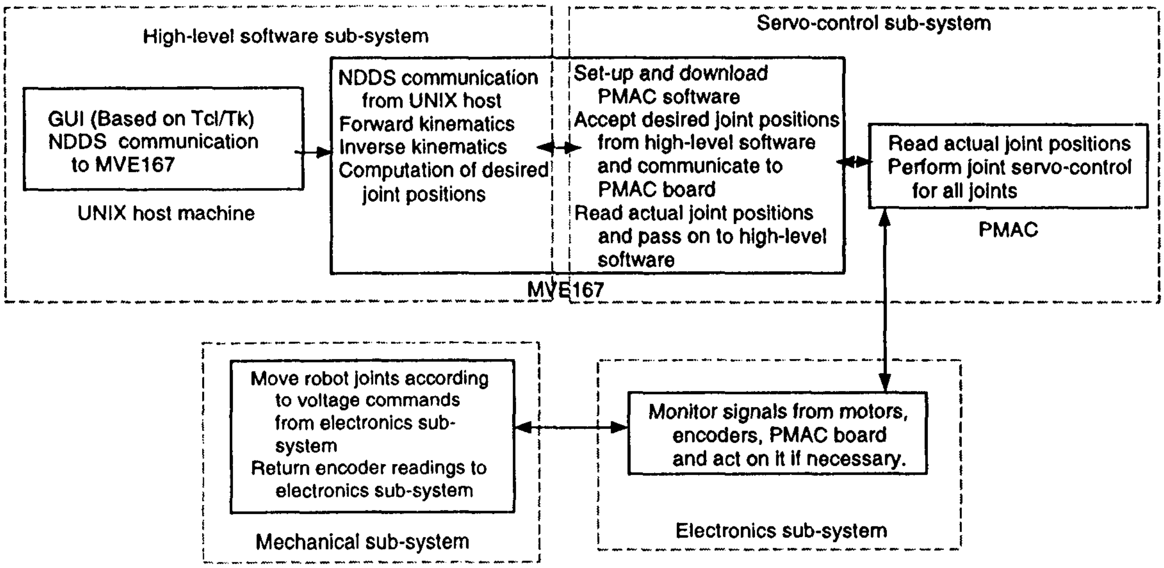

Figure 2 Sub-systems of the RAMS system.

The mechanical sub-system consists of the master and slave robots. The master device is able to sense its handle position in six degrees of freedom with an accuracy of 30 microns. The slave robot can position a surgical instrument mounted at its tip to an accuracy of 12 microns in six degrees of freedom.. The workspace of the slave robot is a hemisphere with a diameter of 30cm while the master has a 5cm by 5cm by 5cm cubic workspace. The electronics sub-system consists of motor amplifiers, a safety electronics module and its associated relays to monitor faults in the system and to act on them. These elements ensure that a number of potential error conditions are handled quickly and gracefully. The servo-control sub-system consists of both hardware and software. The hardware is the DSP-based PMAC servo-control boards to control the joints of the master and slave arms and a Motorola MVME-167 (MC68040 processor based) board installed in a VME chassis. The software on the servo-control boards positions the joints of the slave arm and determine the torque at the joints of the master arm based on signals from the high-level configuration software sub-system. Software on the MVME-167 board interfaces signals from the high-level configuration software sub-system to the servo-control sub-system. The configuration control and user interface software sub-system reads inputs from a graphical user interface and sets the appropriate configuration parameters on the RAMS system, compute the kinematics and high-level control functions and determine the signals with which to drive the master and slave arms. The engineering design of the RAMS system has been reported with greater detail in Charles, et al[6]. A photograph of the RAMS system is shown on Figure 3.

We use a fairly simple and conventional control method to achieve master-to-slave control. The master robot forward kinematics algorithm computes the master handle position and orientation from master joint positions read in from the servo control cards through shared memory. The handle incremental motion is computed then filtered (based on the GUI filter bandwidth setting). It is then scaled (based on a GUI parameter setting) and transformed to a slave base-referenced coordinate frame. The incremental motion is added to the slave tip position and orientation (computed from measured slave joint positions by the slave forward kinematics algorithm). The new desired slave tip position and orientation is fed to an inverse kinematics routine that computes the corresponding joint positions. The result is used to command the new positions of the joints of the slave through shared memory and the servo control boards. Although the

RAMS system is currently capable of reflecting forces measured from the slave robot tip back to the master handle, force feedback was not used in the experiment because it had not been implemented at the time.

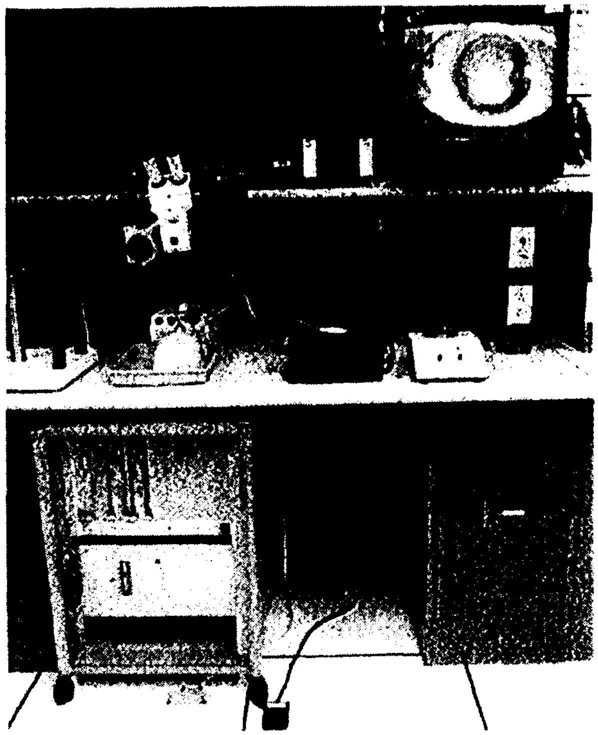

Figure 2 Photograph of a prototype of the RAMS system.

3. Evaluation Experiment and Results

In this section we report on a pilot study conducted at the Doheny Eye Institute in the University of Southern California School of Medicine and at JPL to determine the advantages of the RAMS system over manual performance in a simple probe positioning task. Dr. M. Siemionow, a hand surgeon at the Cleveland Clinic Foundation, evaluated an early prototype of the RAMS system in 1997. A single subject (a microsurgery resident) performed a comparison of manual versus telerobotic operation of seven microsurgical procedures. Dr. Siemionow reported that in five of the seven procedures tested, the RAMS prototype performed better than manual techniques[16]. In contrast to the Cleveland Clinic study, a randomized variables study with multiple subjects was performed to obtain a statistical evaluation of the performance of the RAMS system. The goal of the experiment was to compare the ability of human subjects to position a probe precisely in a microscopic field using the RAMS system against performance of the same task while manually holding a similar probe. Rather than use complex microsurgical procedures as tasks to be performed in our experiment as was done in the Cleveland Clinic study, we chose a simple probe-positioning task. The reasons are:

- Performance is measured by a *blind* data collection system so objective measures of the difference in performance could be implemented.
- The aspect of performance tested (ability to position precisely) is well defined. Human manual dexterity is a complex motor skill and we wanted to limit ourselves to simple aspects of it.
- The simplicity of the task enabled multiple repetitions to be performed by each subject to obtain a statistical measure of the difference between manual and telerobotic performance of the task.
- The conduct of the experiment was automated and controlled by the data collection system thereby simplifying the experimental procedures. And the simple procedures make it easy to enforce identical experimental conditions for the subjects within the randomized variables.

- A robust *task board* was designed and fabricated to withstand repeated abuse during training and experiment. It would have been difficult to keep a more complex *task board* from deteriorating during the experiment. Repetitions of the tests were easily performed because of the minimal set-up time required.

3.1 Description

The experiment conducted was to have human subjects perform a probe tip-positioning task. Two options were available for performing the task – *manual positioning* and *telerobotic positioning*. The set-up, named *manual positioning*, is drawn on Figure 4. A microscopic task board was designed with targets, each 0.003" in diameter and 0.025" apart, arranged in a rectangular 4 by 6 array on a grid as shown on Figure 5. The task for the subjects was to touch the targets in a specified sequence as shown by the gray arrows without touching the background using a hand-held probe. In the *telerobotic positioning* mode, the subjects performed the identical task but used the telerobot input device controlling an identical probe held by the slave robot.

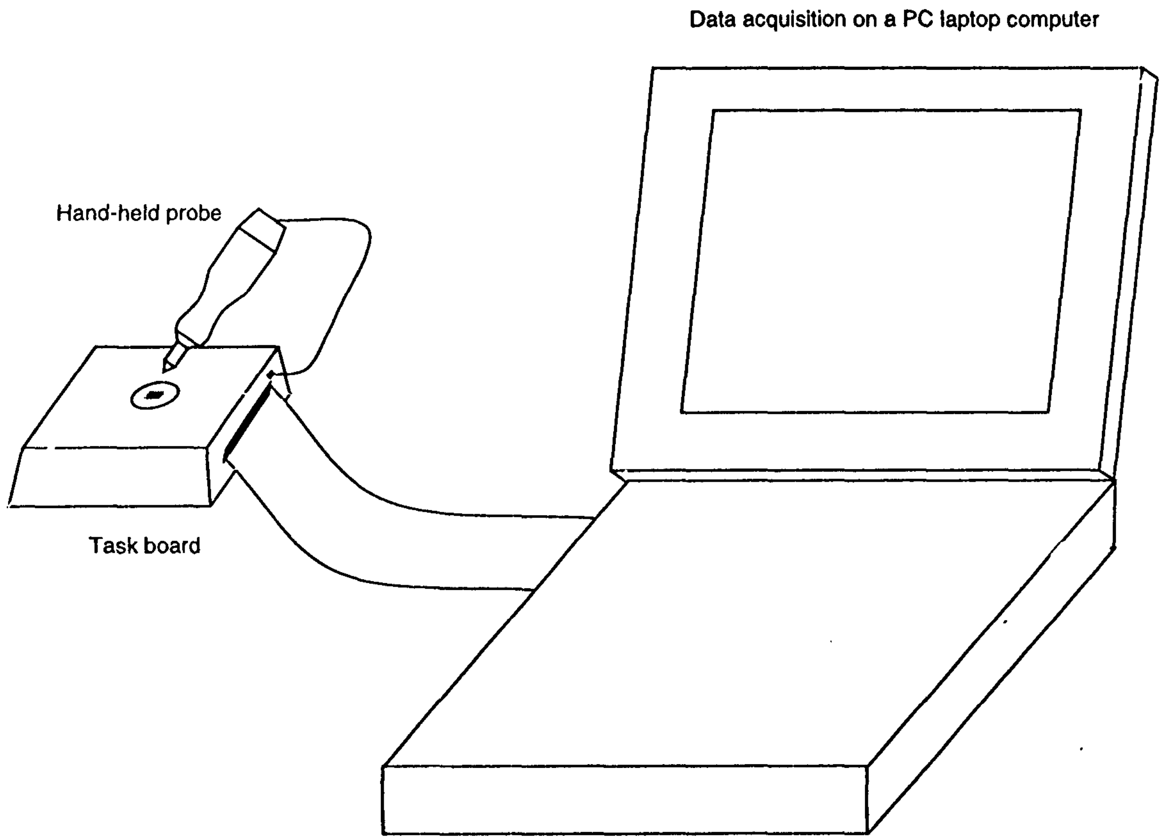

Figure 4 Data collection for probe positioning task shown in *Manual* configuration.

Three groups of subjects were selected: Group 1 - seven 2nd year medical students at the USC School of Medicine, Group 2 - seven ophthalmology surgeons at the Doheny Eye Institute and Group 3 - nine robotics engineers at JPL. Training and experiment were conducted in one continuous session. A pre-experiment test showed that subjects required more training with the robotic system than in the hand-held probe mode to reach a leveling-off of their performance improvement. Due to the limited availability of the medical students and surgeons, the training time for these two groups of subjects was limited to performing 8 repetitions of the task with the telerobotic system and 2 repetitions with the hand-held probe. The complete session for a subject lasted an average of about 30 minutes. The tests were conducted at the Doheny Eye Institute. The tests on the JPL robotics engineers were conducted at JPL and their training was to perform 18 repetitions of the task with the telerobotic system (twice the training of the medical students and opthalmology surgeons) and 2 repetitions with the hand-held probe. The complete session for a subject lasted an average of about 60 minutes.

Data collected were the number of errors (contacts between the probe and the background) and time taken to complete the task. The data was collected by the data acquisition system implemented on a laptop computer. The experimenter initialized the data acquisition system at the start of each task. The subject started the clock on the timing of the task and the collection of data by touching the first target with the tip of the probe. The subject then proceeded by touching the next target with the probe tip upon hearing an audible beep indicating that he had successfully touched the current target. The process was repeated for the 10 targets. Errors were logged as the accumulation of contacts at the data acquisition sample rate between the probe and the background. The task was completed by successfully touching the targets in sequence until the final target was touched. This stopped the clock on the timing of the task and the accumulation of errors in performing the task.

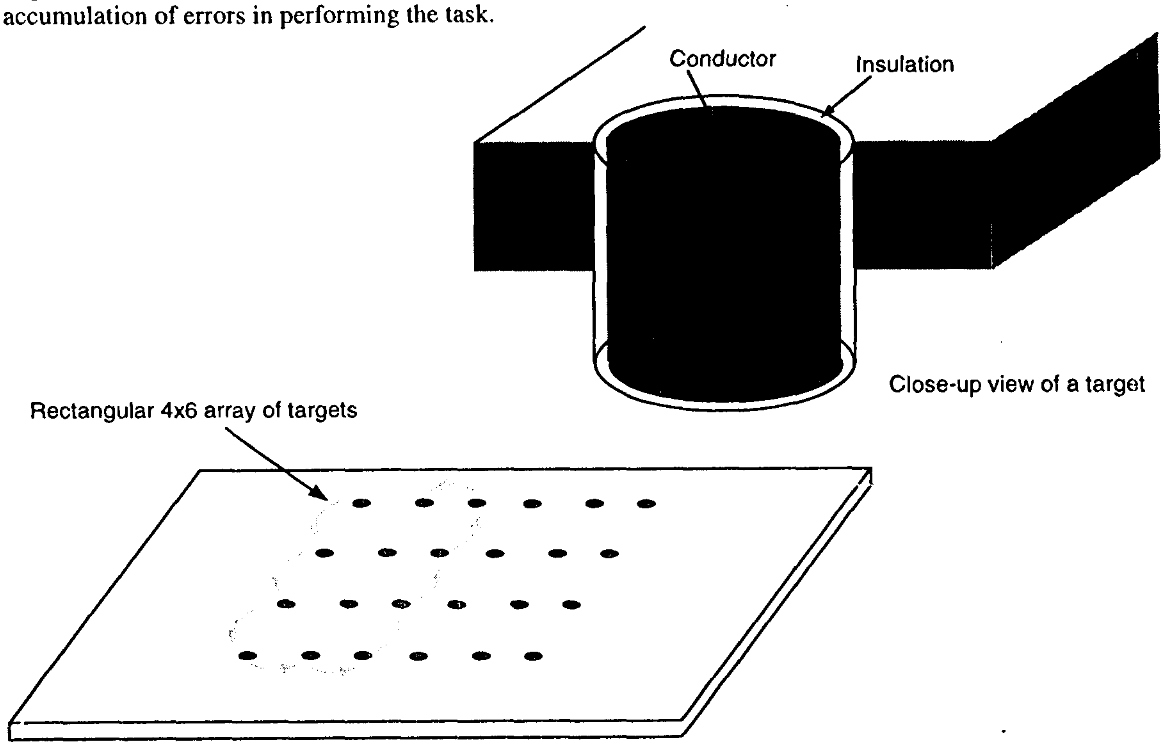

Figure 5 Rectangular array of targets for probe positioning task and close-up of target.

Tremor filtering parameters on the telerobotic system were varied during the experiment to determine if alternatives in those parameters affected the performance of the subjects when using the telerobotic system. The tremor filter setting was chosen to limit the hand motion to either 5Hz or 30Hz. The 30Hz setting was chosen to pass through to the instrument tip the full bandwidth of the subject's hand motion. The 5Hz setting was conservatively chosen to eliminate tremor. In the human arm, tremor is reported to be on the order of 6 to 12 Hz[17]. In the braced hand configuration used in this experiment, tremor has been reported to be in the 7 to 12 Hz range[18]. Subjects were also asked to provide feedback on a questionnaire at the end of their experimental session on their impressions of the experiment and their performance in the different modes of operation offered.

A typical session with a subject at the Doheny Eye Institute (and at JPL) went as follows:

- The procedure to be followed in conducting the experiment was verbally described to the subject.
- The task was performed once using the telerobotic system as a trial run to familiarize the subject with the procedure.
- Data was collected during 2 trials (3 at JPL) of manually performing the task.
- Training was provided in 2 trials (3 at JPL) while manually positioning the probe.

- A training procedure for the use of the RAMS system followed. The tremor filter settings were randomly set to either 5Hz or 30Hz respectively for the next 8 trials (18 at JPL)
- The experiment was run with data collection for analysis. 2 tests (4 at JPL) were run with one setting of the tremor filter then another 2 tests (4 at JPL) were run with the other setting of the tremor filter.
- The subject filled out a questionnaire on the test.

3.2 Data Analysis and Results

Means and standard deviations for the respective groups for normalized time taken to complete the test are shown on Figure 6. Normalized errors incurred during the test comparing telerobotic to manual performance are shown on Figure 7. Normalization was done in the data by dividing the respective data by the average of the mean of the manual and RAMS data The reason for normalization is to determine a performance indicator reflected improvement or degradation in performance with respect to the capability of the subject. The data from 1 subject from Group 3 was discarded as an outlier because it represented data points three standard deviations from the mean. The data is presented for the combined pool of subjects (G-All) and for the groups (G-1, G-2, G-3) of subjects.

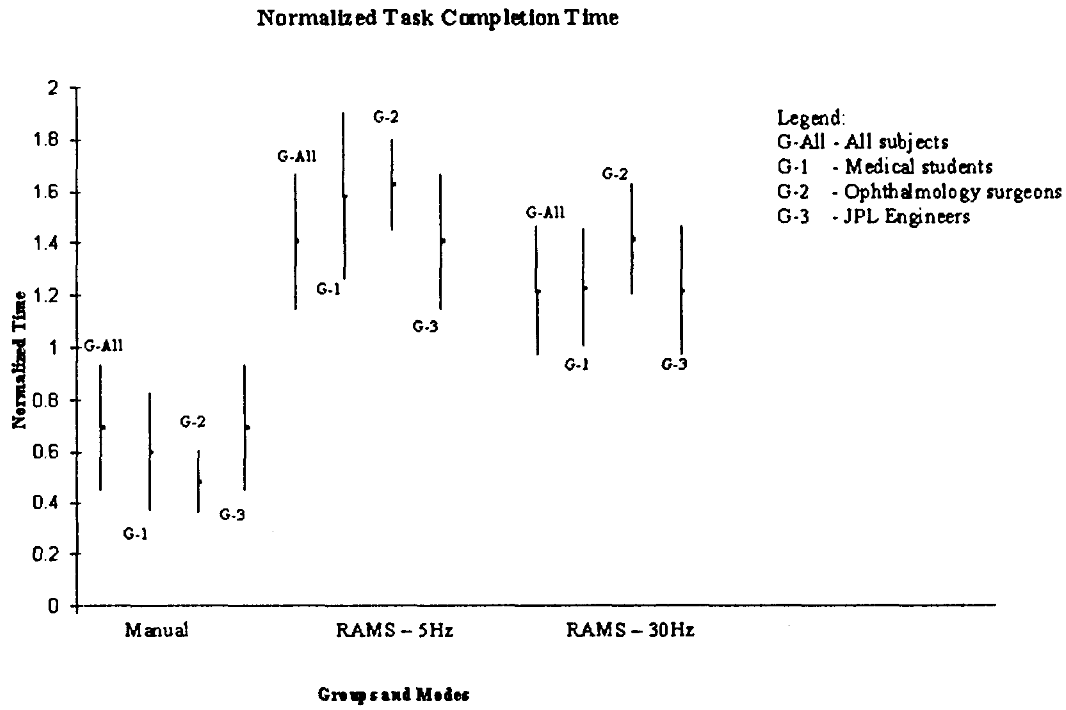

Figure 6 Normalized task completion times (mean and std. dev.).

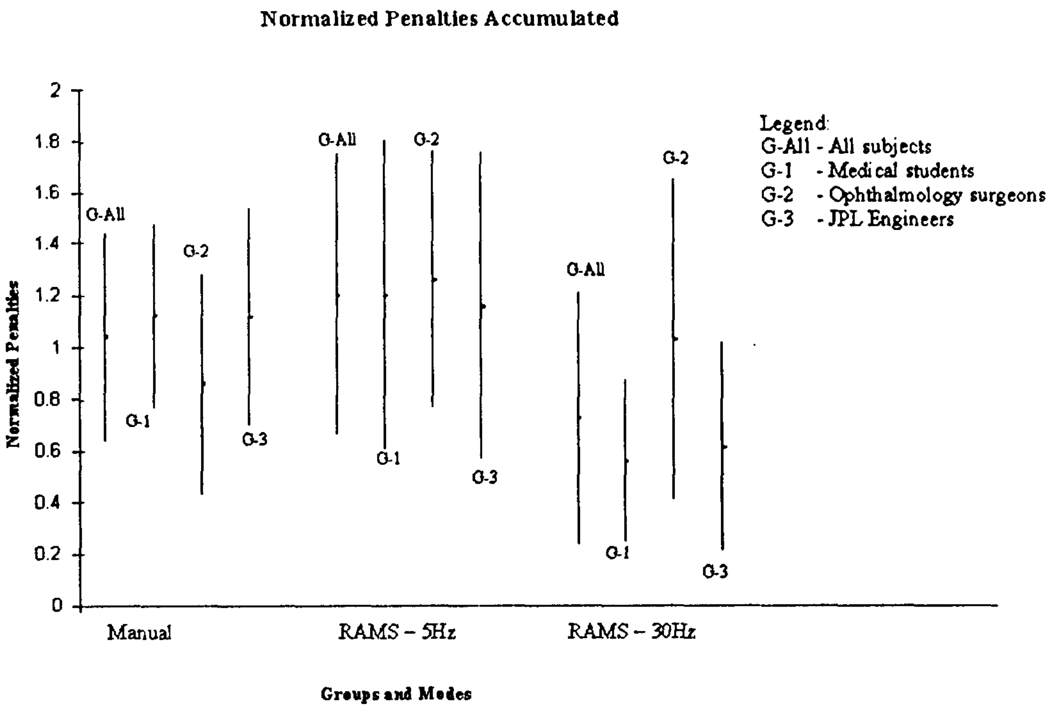

Figure 7 Normalized penalties accumulated (mean and std. dev.).

On the plots above, the *Manual* mode refers to the mode of performing the task with the hand-held probe. The *RAMS-Combined* mode is the combined data for both 5Hz and 30Hz tremor filtering using the RAMS system. The *RAMS-5Hz* mode represents data from the use of the RAMS system to perform the task with the tremor filter set to cutoff motion above 5Hz and, similarly, the *RAMS-30Hz* mode is with the tremor filter set to cut-off motion above 30 Hz.

The data for normalized task completion times clearly show that subjects performed the tasks significantly more quickly with the manual mode. The data for normalized penalties accumulated are more interesting and a single factor ANOVA was performed on the penalties accumulated data to discern differences between the alternative modes available. We use the P-value to represent of the difference between any two sets of data. If the two populations really have the same mean, the P-value is the probability that random sampling would result in means as far apart (or more so) as observed in the experiment. A small P-value indicates that the probability is small. For statistical significance, a P-value of 0.05 or less is generally accepted as a significant difference i.e. unlikely to be produced by random sampling of distributions with the same mean. The results are presented in Table 1 below. Tests that had a significant result are shown in bold.

Table 1 ANOVA test results of operator performance comparing pairs of alternative modes of performing the task.	**P-Value**
For all subjects – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *Manual* mode	**0.021**
For Group 1 - *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *Manual* mode	**0.008**

For Group 2 - *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *Manual* mode	0.543
For Group 3 – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *Manual* mode	**0.019**
For all subjects – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *RAMS-5Hz* mode	**0.003**
For Group 1 – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *RAMS-5Hz* mode	**0.026**
For Group 2 – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *RAMS-5Hz* mode	0.458
For Group 3 – *RAMS-30Hz* mode resulted in fewer normalized penalties accumulated than the *RAMS-5Hz* mode	**0.036**

At the end of each session, the subjects were asked to fill out a questionnaire. Two easily quantifiable questions asked were:

1. Did the subjects feel that the RAMS system improved or worsened their performance compared to the manual positioning of the probe?
2. Did the subject feel that with more training they would be able to improve their performance using the RAMS system compared to the manual positioning of the probe?

The subjects were also asked to rate on a scale of 1 to 5 (1 = highly unconfident, 5 = highly confident), their confidence using the *Manual*, *RAMS–5Hz* and *RAMS–30Hz* modes for performing the task.

The response were:

- In the group of medical students (Group 1), 4 felt that the RAMS system improved their performance and 3 were either not sure or felt that they were the same.
- All subjects in Group 1 felt that their performance with the RAMS system would be better with more training.
- In the group of surgeons (Group 2), 4 felt that the RAMS system improved their performance and 3 felt that it worsened their performance.
- 5 out of 7 surgeons felt that their performance would improve with training, 2 felt that they were either not sure or did not know.
- In Group 3 (JPL engineers), 6 out of 9 subjects felt that their performance improved with the RAMS system, 2 were either not sure or did not know and 1 felt that his performance worsened.
- 7 subjects in group 3 felt that their performance would be better with more training and 2 were either not sure or did not know.

The ratings results are plotted on Figure 8 below and the corresponding ANOVA results shown on Table 2.

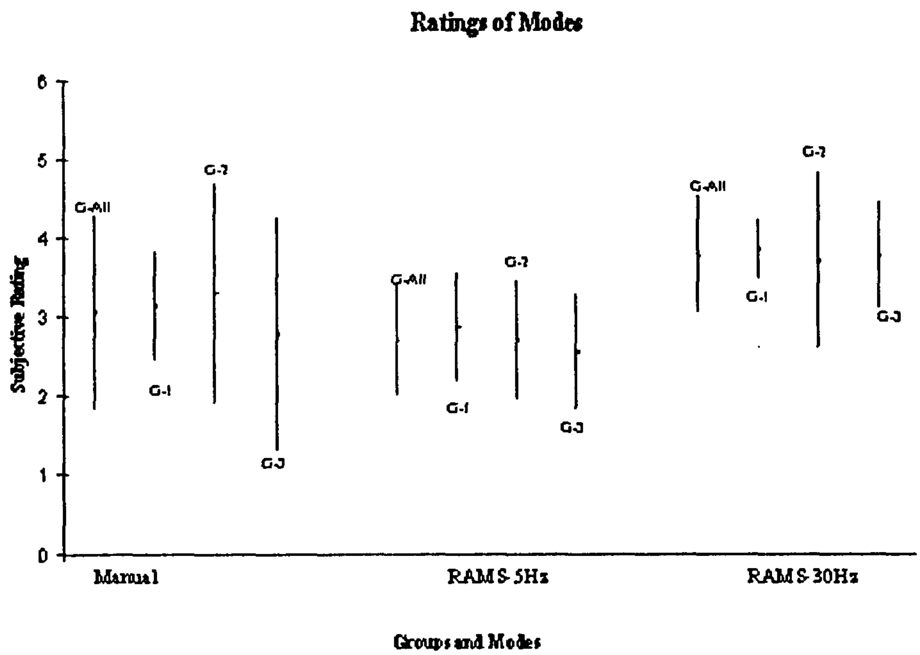

Figure 8 Subjective ratings of different modes (mean and std. dev.).

Table 2 ANOVA test results of comparison of subject ratings between pairs of modes	**P-value**
For all subjects – Subjects felt more confident using the RAMS-30Hz mode versus the Manual mode.	**0.017**
For Group 1 – Subjects felt more confident using the RAMS-30Hz mode versus the Manual mode.	**0.033**
For Group 2 – Subjects felt more confident using the RAMS-30Hz mode versus the Manual mode.	0.534
For Group 3 – Subjects felt more confident using the RAMS-30Hz mode versus the Manual mode.	0.083
For all subjects – Subjects felt more confident using the RAMS-30Hz mode versus the RAMS-5Hz mode.	**0.000**
For Group 1 – Subjects felt more confident using the RAMS-30Hz mode versus the RAMS-5Hz mode.	**0.006**
For Group 2 – Subjects felt more confident using the RAMS-30Hz mode versus the RAMS-5Hz mode.	0.073
For Group 3 – Subjects felt more confident using the RAMS-30Hz mode versus the RAMS-5Hz mode.	**0.002**

The following summarizes the results and it is followed by a discussion of the details.

- Task completion times are significantly shorter in the *Manual* mode than with using the RAMS with either the *30Hz* or the *5Hz* tremor filter.
- The performance of the group of ophthalmology surgeons (Group 2) did not indicate any conclusive advantage with any of the modes of performing the task.
- Groups 1 and 3 incurred significantly fewer normalized penalties with the RAMS system set to the 30Hz tremor filter then in the *Manual* mode, i.e. the RAMS system was shown to increase positioning accuracy relative to that achieved manually.
- The pooled groups of subjects and Groups 1 and 3 incurred fewer normalized penalties with the RAMS system set to the *30Hz* tremor filter than to the RAMS system set to the *5Hz* tremor filter.
- The subjects felt more confident using the RAMS system (30Hz) than the manual mode.
- The subjects felt that their performance with the RAMS system would be even better if they were given more training on it.

4. Discussion

The experiment showed that the time taken to perform the precision positioning task was clearly longer when using the RAMS system. The results on errors occurred (normalized penalties accumulated) was mixed. The tremor filter set to limit hand motion to below 5Hz appeared to degrade performance of most subjects even though it was designed to eliminate tremor in hand motion. Even though the groups of medical students (Group 1) and JPL robotics engineers (Group 3) did have a significant advantage with the RAMS system set to the 30Hz filter, the group composed of ophthalmology surgeons appeared to not have a significant advantage when using the 30Hz tremor filter in the RAMS system. Groups 1 and 3 performed significantly better with the RAMS system with its tremor filter set to allow hand motion below 30Hz through than with the hand held probe. The ophthalmology surgeons did not have a significant performance improvement when comparing the RAMS system to the manual mode.

The results from the questionnaire confirm the earlier conclusions. Generally, subjects significantly preferred the RAMS system with the 30Hz tremor filter setting over the RAMS system with the 5Hz tremor filter. For the pooled groups of subjects, there is also a significant preference for the RAMS system with the 30Hz tremor filter over the Manual mode. There was no indication of preference for the group of surgeons, however.

The surgeons who participated in the experiment were available only as their schedules permitted. In some cases, their experimental session was interrupted by the urgent needs of the subject's patients and the experimental session was resumed when the subject became available again. In most cases, the subjects were in a hurry to complete the test. Some also appeared to be nervous about measurements made on their manual dexterity. These effects could have had a significant impact on their performance.

The experiment that we conducted has provided much practical insight into issues in conducting such tests. These include:

- Subjects had varied preferences in the configuration of the experimental equipment (e.g. position of the input device, position of the microscope, etc) and it would have been advisable to have the configuration be easily adjustable to adapt to the subject's preferences.
- The conditions under which subjects participated greatly affected their performance. The surgeons in our study participated under relatively stressful conditions. Performance was also dependent on the motivation of subjects to perform well. A third factor that affected performance was the amount of training subjects received. These factors should be controlled to minimize their effect on the experimental result.
- Alternative measures provide different indices of performance and the metric used should accurately reflect the performance index of interest. The measure of penalties in this experiment accumulated errors at a fixed rate over time so that a slow experimental run of exactly same motion would result in a greater number of penalties.
- The experimental equipment should have replacement parts for elements that may wear out or break down during the experiment.
- Thorough testing of the equipment in experiment-like conditions can provide experience that is helpful when running the actual experiment. Using a research prototype in these tests resulted in issues of

reliability and robustness of the prototype and the experimental fixtures in addition to the usual problems of dealing with the variability and performance of human subjects.

The research effort to develop the RAMS system was recently completed at JPL so confirmation of these results with further experiments on the same hardware is no longer possible. However, the results learned from this development and the experiment conducted indicate that there is potentially a significant benefit to be gained from a telerobotic tool to assist surgeons perform microsurgery.

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